Development of An Empirical Model for MDF Hot Press and Comparison with A Fundamental Model

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ABSTRACT

Hot pressing is one of the critical operations during manufacturing of medium density fibreboard (MDF). In the hot pressing, moisture, mass transfer, heat transfer and fibre densification interact, resulting in continuing changes in mat physical, chemical and mechanical properties.

In order to better understand the hot pressing process, both empirical investigation and theoretical modelling have been performed. The advantage of the empirical approach is that it takes less time although the result is applicable only in the range of conditions tested. In the theoretical modelling, the behaviour of wood composites is mathematically expressed by applying the fundamental laws including heat and mass transfer within the panel, the stress and strain development, and creep behaviour of the fibre mat, and the curing kinetics of the resin. The fundamental model can be solved to predict the outcome for a wide range of raw material properties and pressing conditions, but the theoretical model needs validation before practical application.

This paper firstly presents an empirical model developed based on results for panels made under different pressing conditions in a pilot-scale press. This empirical model is used to determine the effects of mat material variables and pressing conditions on important panel properties. These properties include peak and core density, modulus of rupture (MOR), modulus of elasticity (MOE) and internal bonding (IB). The core temperature and internal pressure are also quantified. The predicted properties from the empirical model are then compared with the simulation results from a fundamental model described in a separate papers. From the comparison, different modelling approaches in the field of wood composites are better understood and the advantages and disadvantages of each approach are analysed.

Keywords: MDF, wood composite, vertical density profile, empirical modelling

INTRODUCTION

Two different approaches to model the hot pressing process of wood based composites can be found in the literature. The first is the empirical modelling approach, which employs statistical methods to link material and process variables to output parameters, such as mechanical properties of the final product. The second uses fundamental principles to describe the relevant physical or chemical processes. Both these approaches will be considered here.

The first fundamental model based on heat and mass transfer model, and physical principles was developed by Humphrey (1982), which included vapour convection, heat conduction and convection, and phase change within the pane during pressing. The model predicted temperature, vapour pressure and moisture content development during hot pressing. A cylindrical coordinate system was employed to model a circular mat, so that cross-sectional as well as radial heat and mass transfer was accounted for. The basis of the model was a modified finite difference approach. The predicted data agreed well in trend with those observed experimentally for particleboard.

Hubert and Dai (1998) presented a one dimensional model for simulating hot pressing of OSB using an implicit finite element modelling approach. Mechanisms included were vapour convection, conductive and convective, heat transfer, phase change, adhesive cure and mat densification. The visco-elastic behaviour of the mat was neglected. Hubert and Dai (1998) compared model predictions of various parameters with measured data and reported that typical trends are predicted correctly, but that some magnitude discrepancies exist.

For MDF, a three dimensional unsteady state model was presented by Carvalho and Costa (1998) describing the heat and mass transfer and predicting the spatial and time evolution of temperature, moisture content, steam pressure and relative humidity. Recently, the model developed by Humphrey (1982) for the hot-pressing of particleboard in a batch press has been improved and extended to the continuous process by Thomen (2000). However this model ignores the influence of resin cure.

The pressing operation in composite wood is one of the most important and complicated operations in wood composites manufacture (Bolton and Humphrey, 1988; Kamke and Casey, 1988; Wang, 1992; Winistorfer, 1992). Complicated interactions of dynamic conditions occur during pressing, including heat transfer, moisture movement, development of gas pressure, wood stress relaxation, wood consolidation, resin curing and bonding between flakes, and eventual development of a non uniform consolidation-induced density distribution through the panel thickness. The dependence of some of the mechanical properties of MDF panels on the panel density is given in Gupta.et.al. (2005).

The objectives of the present study were to develop an empirical model to investigate the relationships between the mean density, vertical density profile, and the physical and mechanical properties of MDF. The quantitative understanding of the above correlations is fundamental and vital for the attempts in simulating the density profile for the boards with desired properties for specific end uses. The regression equations obtained in the experimental work form an empirical model, which aims to predict the mechanical properties of the panel for given values of fibre moisture content, resin content and press cycle. Matlab is used to solve the model equations and the simulation results are compared with those from a fundamental model which is described in detail in separate papers by Gupta et al. (2006a, 2006b).

MATERIALS AND METHODS

Raw materials and board manufacturing

The resinated fibres of *Pinus radiata* were supplied by Carter Hold Harvey Pine Panels, Rangiora, New Zealand. The moisture content of the fibres was 10.5 % and the resin content was 10.5%, both being based on the oven dry weight of fibres. The resin used was Urea-Formaldehyde. Once the fibres were received, the tests were performed in the same day to manufacture 12 MDF boards on a pilot press in the Department of Chemical and Process Engineering, University of Canterbury.

The dimensions of the boards made were 300 mm x 300 mm with the target board thickness being from 10 mm to 13.5 mm. All of the boards had the same amount of fibres and thus different thickness of the board had different density. This arrangement will also help to study the rate of increase of peak and core density for similar pressing conditions. During making the board, a thermocouple wire was inserted in the mid-thickness of the board after pre-pressing to measure the core temperature. The core temperature, platen pressure and position were recorded at 10 second intervals. The platen temperature was maintained at $180^{\circ}C$.

MDF Press Cycle:
The press cycle used for making the boards in this study was similar to that in the batch pressing of commercial boards. The total pressing time was 150 seconds in order for the core temperature to maintain above 100°C for the few seconds needed for the resin to cure. Fig. 1 shows the platen pressure through the press cycle, while Fig. 2 shows the movement of platen position with time for a selection of the boards.

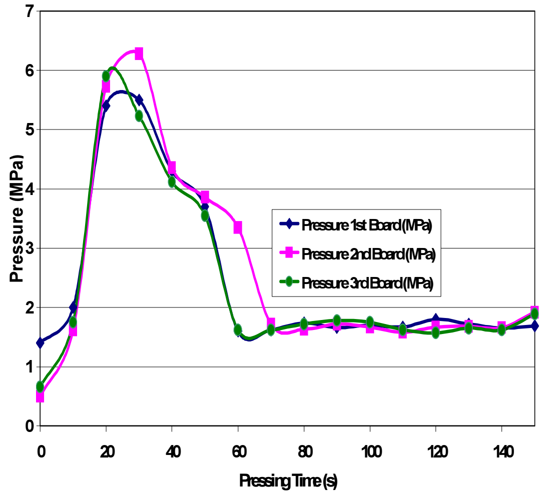

Fig.1 Change of platen pressure with time

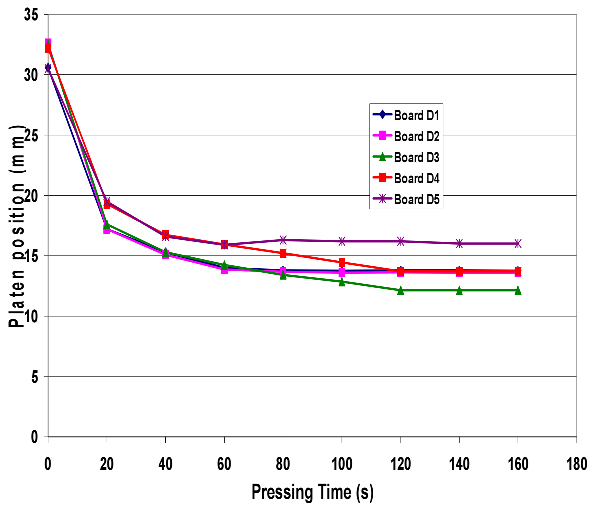

Fig.2 Change of platen position with time

MDF Testing:
The boards were tested for their physical properties. From each board made, a square of 50mm x 50mm was cut and placed in a density profile X-ray scanning machine (ProScan) to obtain its vertical density profile (VDP) graph. The ProScan profiler works by measuring the amount of gamma radiation transmitted through the sample as emitted by a low energy radiation source. After the VDP test, both surfaces of the sample were sanded to remove the precure layers of the board. The samples were then tested for internal bonding, modulus of rupture (MOR) and modulus of elasticity (MOE). All tests were conducted according to the procedure specified in AS/NZS 4266.5 (2004). The details of the experiment and measured results are given in Table 2 at the end of this paper.

THE EMPIRICAL MODEL AND RESULTS

Regression Equations:
From the experimental results, the following regression correlations have been obtained to relate various board properties.

1. Board peak density (PD) as a function of board mean density (MD):

$$PD = 0.529MD + 513.65 \qquad R^2 = 0.5742 \qquad (1)$$

2. Board core density (CD) as a function of board mean density:

$$CD = 1.324MD - 268.09 \qquad R^2 = 0.9405 \qquad (2)$$

3. Board Internal Bonding(IB) as a function of board mean density:

$$IB = (3.601\times10^{-6} MD^2) - (1.672\times10^{-3} MD) + (1.622\times10^{-1}) \qquad R^2 = 0.8523 \qquad (3)$$

4. Board Internal Bonding(IB) as a function of Core density(CD)

$$IB = 2.886\times10^{-7} CD^{2.274} \qquad R^2 = 0.8949 \qquad (4)$$

5. Board Modulus of Rupture (MOR) as a function of board mean density

$$MOR = 0.0771MD - 20.596 \qquad R^2 = 0.7999 \qquad (5)$$

6. Board Modulus of Elasticity(MOE) as a function of board mean density

$$MOE = 4.0701MD - 337.91 \qquad R^2 = 0.7926 \qquad (6)$$

7. Variation of Core temperature(CT) with time (t)

$$CT = -0.0071t^2 + 2.1515t - 53.214 \qquad R^2 = 0.9885 \qquad (7)$$

Core temperature is below $30^\circ C$ until 30 sec and $104^\circ C$ after 120 sec. Equations predicts core temperature between these time limits.

Correlation of Peak and Core density with Mean density: As observed from Figure 3, there is good a relationship between peak density and mean density for a given press cycle. It was found that in the initial few seconds the increase in peak density was fast and once it approaches 800 kg/m^3 , the increase becomes slow. The core density keeps on increasing in a straight line for the tested press cycle with constant moisture content and resin amount.

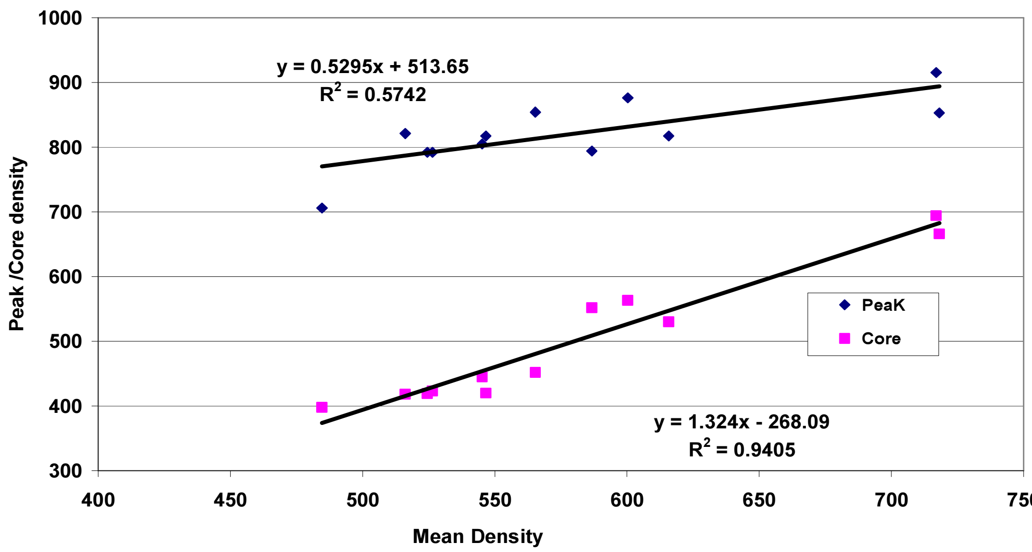

Fig 3. Correlations of the peak density and the core density with the mean density

Variation of Internal Bonding with Core density: It was observed that internal bonding is slightly better related to core density than to the mean density as shown in Figures 4 and 5.

The IB value increases with both the mean and core densities. The breaking within the board normally occurs at the weakest point where the density is the lowest and this point is located in the core zone of the board. However, it was observed during the IB test that the weakest point is not always right at the mid-thickness of and the board. The breaking occurred at 27% and 30% of the depth from the top of the board for samples D4 and F1 respectively as seen from Table 2.

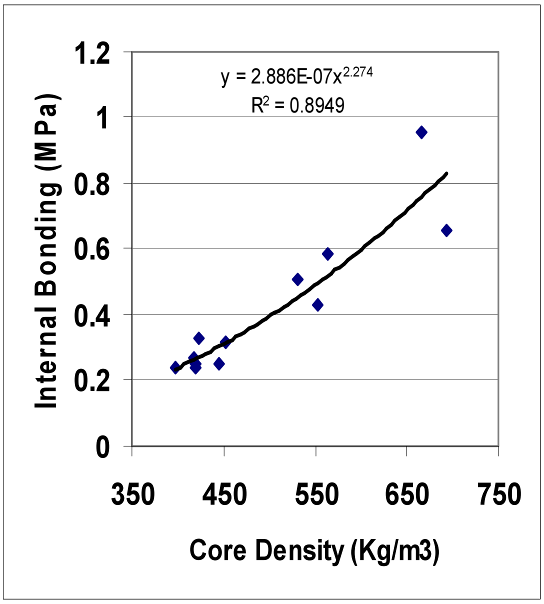

Figure 4 Change of IB with core density

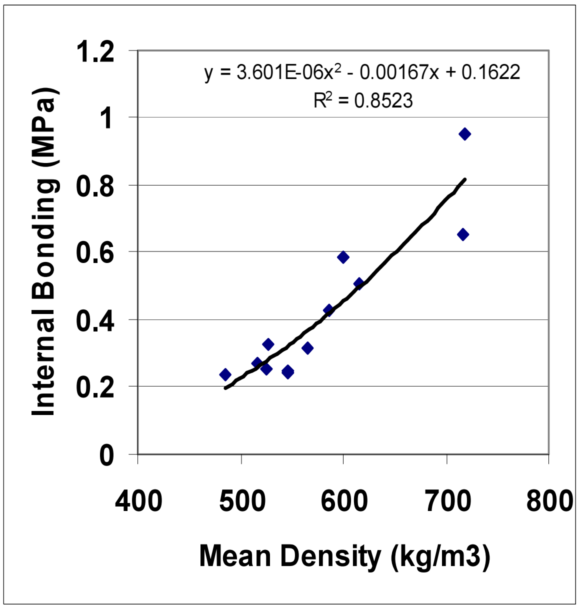

Figure-5 Change of IB with mean density

<u>Modulus of Rupture and Elasticity as A Function of Mean density</u>: The modulus of rupture was found to increase linearly with density as shown in Fig.6. The MOE also increased linearly with the mean density, with a similar correlation coefficient to that for the MOR (see Fig 7).

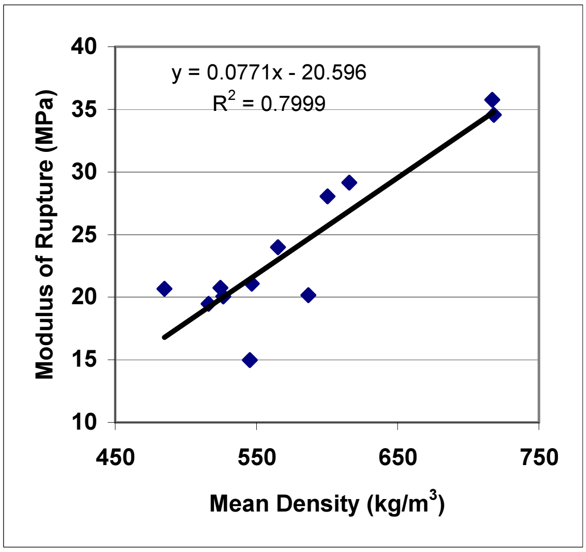

Fig-6 Change of MOR with mean density by experiment

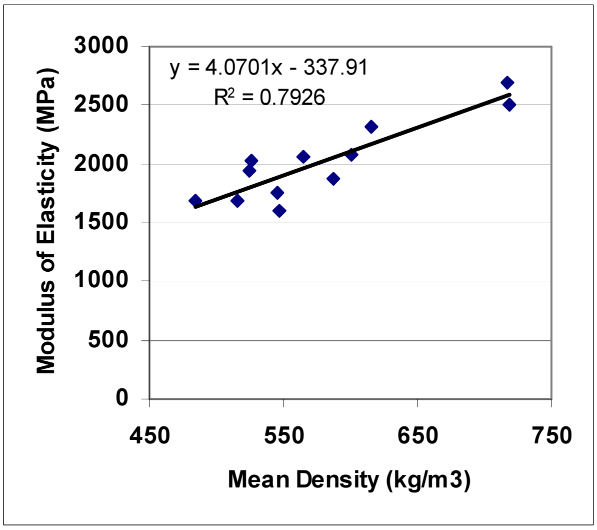

Fig-7 Change of MOE with mean density by experiment

Core Temperature Change with Press Time: The core temperature response is shown in Fig.8 for three boards. It was observed that for the initial 30 seconds there was virtually no increase in the core temperature. After that period, the core temperature rises quite rapidly until it reaches 100 °C when the rate of increase start to slow down dramatically and this phenomenon has been reported for particleboard. The rapid rise in the core temperature from about 30 seconds to 110 seconds is believed to be largely due to the movement of evaporated moisture from the region near the platens to the core as well as the heat conduction. Once the temperature exceeds 100 °C, the heat transfer by conduction becomes significant and further temperature increase will result in more moisture evaporation from the core.

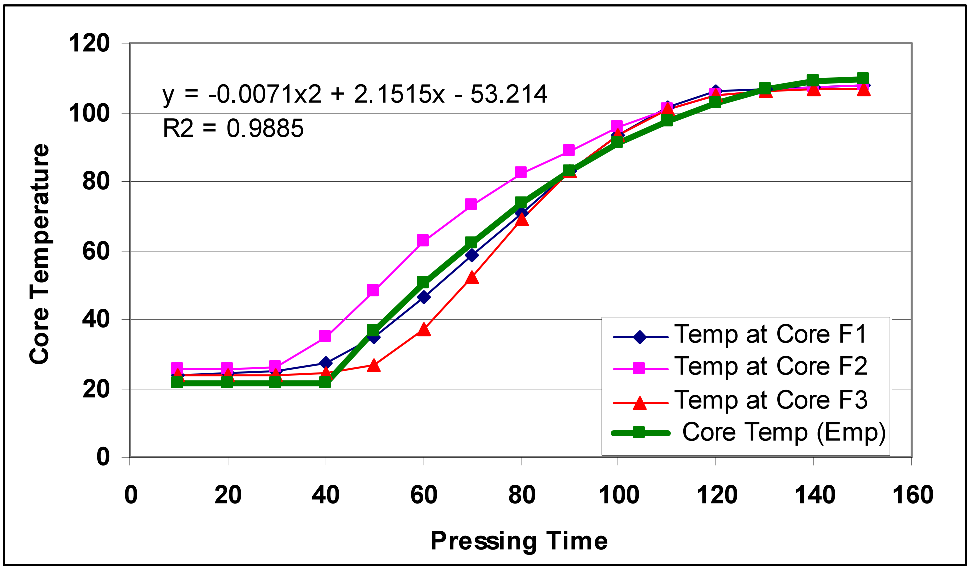

Fig- 8 Change of core temperature with time

COMPARISON WITH A FUNDAMENTAL MODEL

In order to simulate the hot press process; a theoretical model was developed as reported in a separate papers Gupta et al. (2006a, 2006b). The model was programmed using the Matlab software. Due to the complexity of the problem, a modular programming style was chosen. The modular approach ensures the flexibility necessary for incorporation of changes and expansions in the future. In the simulation, the MDF mat is symmetrically divided into two halves and, once the calculation is complete, graphs of output properties for the complete thickness are generated. Input parameters and values for the simulation are given in Table 1 and the simulation results are shown in Figures 9 and 14.

Table 1. Initial parameters for simulation

Panel density	650 kg/m^3
Weight of fibre	0.78 kg
Moisture content	10.5 %
Resin content	10.5 %
Platen temperature	180.2°C
Pressing time	150 s
Press closing time	40 s
Average thickness	13.0 mm
Cycle used	Position
Number of layers in half board	10

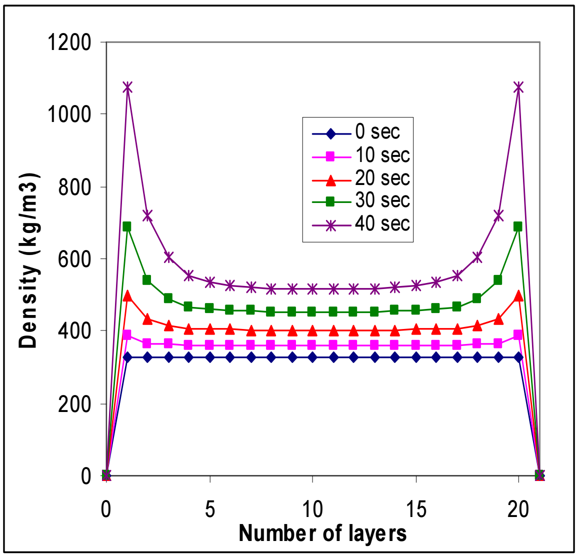

Fig 9. Development of density profile

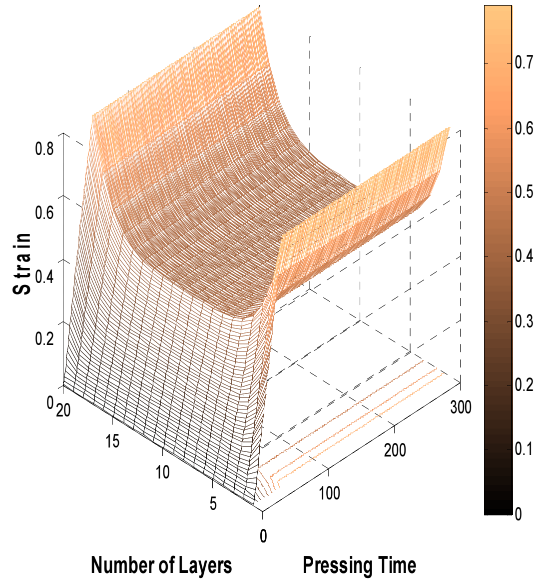

Fig.10. Strain in different layers while pressing

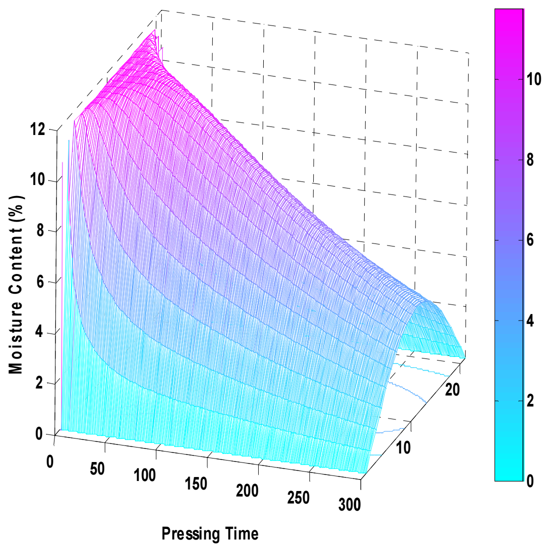

Fig.11 Change in moisture content in different layers during pressing

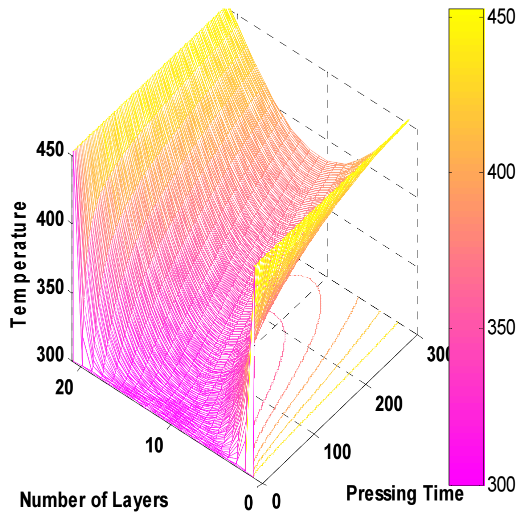

Fig.12. Change in temperature in different layers during pressing

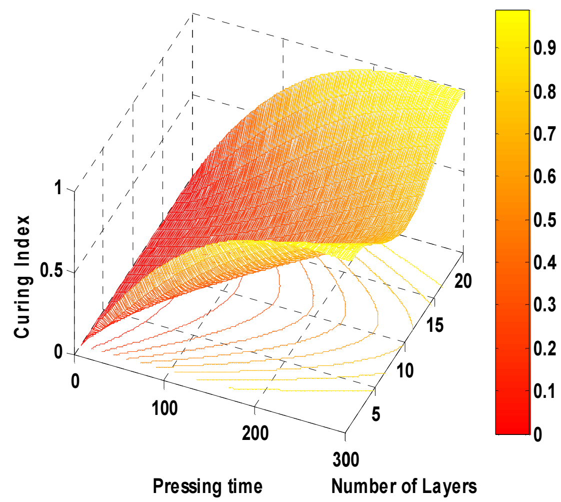

Fig.13 Resin curing in different layers during pressing

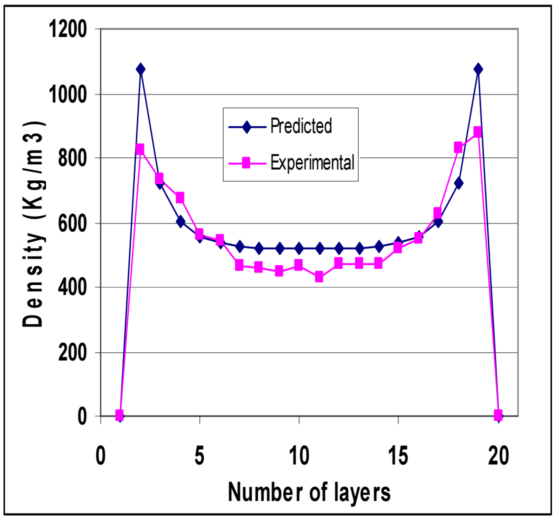

Fig.14.Comparison of predicted and experimental results of density profile

Comparison of Peak and Core densities from both the models: The peak density for the initial eight samples is calculated from both the models and their results are compared with the experimental data obtained by using the Proscan density profiler. It was observed that peak density from the fundamental model is higher than the experimental results. The probable reason is that the equation used to calculate modulus of elasticity Palka (1973) is initially derived for solid wood, which may not give accurate results for low density mat. The equation needs to be refined. The core densities from both the models follow the same trend as that of the experimental data.

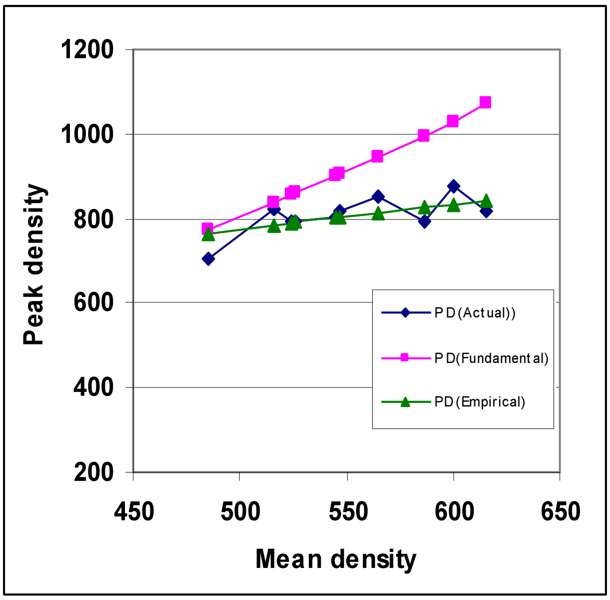

Fig-15. Change of peak density with mean density from the two models

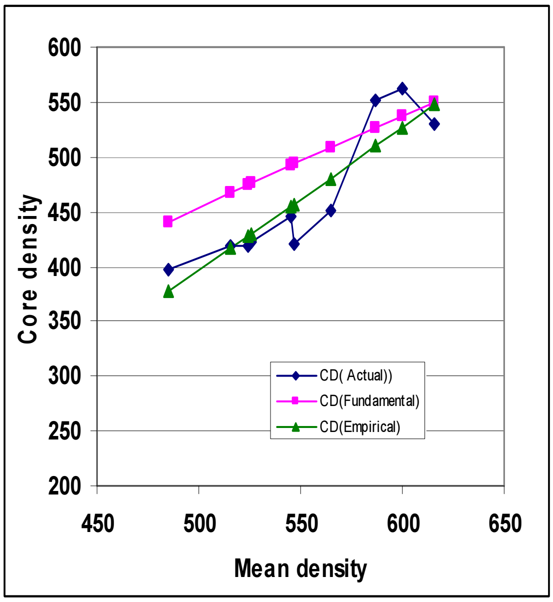

Fig.16 Comparison of core density from the two models

Comparison of Core temperature from both the models: Core temperature is one of the important parameters in the MDF manufacturing, as its value gives the amount of resin cure in the board. The value from both the models overlap, in the beginning the core temp from fundamental is more than the empirical one, but later on decreases. The probable reason for the differences is the heat generated by the compression of mat, loss of heat due to radiation is neglected in the fundamental model.

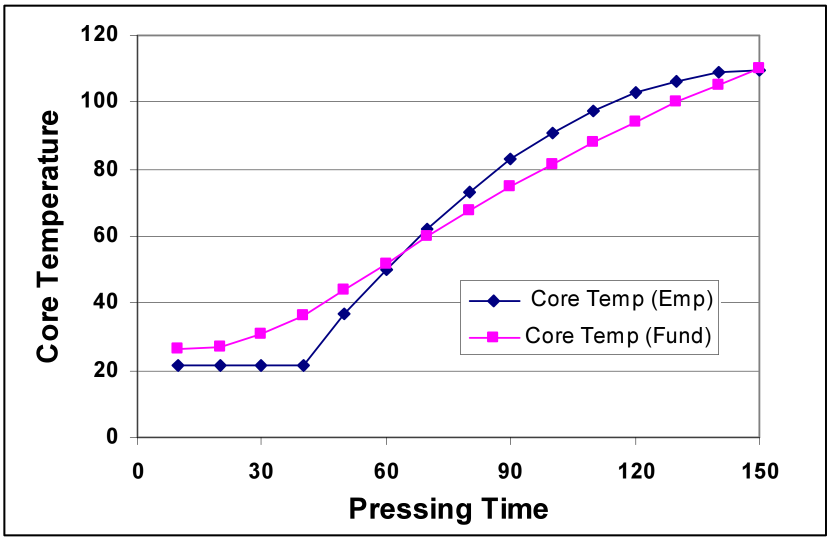

Fig-17 Comparison of core temperature from both the models

CONCLUSIONS

- The empirical model predicts the physical properties for a given press cycle, moisture content and resin content. The results are good for the given set of conditions in which the regression equation are derived but becomes less accurate beyond that condition.
- The model gives good results for thickness ranging from 10 to 13.5 mm and density ranging from 485 kg/m^3 to 718 kg/m^3.
- There is a higher correlation of internal bonding with the core density $(R^2 = 0.89)$ than there is for the mean density $(R^2 = 0.85)$
- Both the MOR (bending strength) and the MOE (bending stiffness) increase linearly with an increase in the mean density with a similar correlation coefficient $(R^2 = 0.80)$.
- Fundamental models are good from the research point of view to develop new press cycle as we can observe all the parameters, which are otherwise very difficult to measure experimentally.
- The predicted peak density from the fundamental model is higher than the empirical one but the core density is the same from both.
- The core temperature from the fundamental model is higher in the beginning but is slightly lower in rest of the pressing time.

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Appendix 1. Data: The experimental data is recorded in table 2.

Table 2. Experimental data

					Density, ρ			
Sample ID	Thickness mm	Mean Density $kg.m^{-3}$	Break from top mm	IB MPa	Peak ρ $kg.m^{-3}$	Core ρ $kg.m^{-3}$	MOR (MPa)	MOE (MPa)
D-1 (Top-4)	11.75	600	5.87	0.58441	876	563	28.06	2072.16
D-2 (Top-3)	11.20	616	5.60	0.50749	817	530	29.14	2313.95
D-3 (Top-3)	9.97	718	4.98	0.95351	853	666	34.56	2506.12
D-4, (Top 4)	11.95	587	3.19	0.42739	794	552	20.15	1871.33
D-5, (Top 4)	13.65	516	6.50	0.27120	821	418	19.48	1679.28
E-1 (Top 4)	13.11	547	6.55	0.24035	817	420	21.08	1593.93
E-2 (Top 4)	13.37	524	6.68	0.25205	792	419	20.74	1949.51
E-3 (Top 4)	13.13	565	6.56	0.31738	854	452	23.99	2057.46
E-4, (Top 2)	10.90	717	5.20	0.65604	915	694	35.77	2694.71
F-1 (Top 3)	13.31	545	3.99	0.25037	805	445	14.98	1760.09
F-2 (Top 2)	13.31	485	6.65	0.23891	706	398	20.66	1696.00
F-3 (Top 3)	13.60	526	6.80	0.32841	792	423	20.07	2024.24